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Extremely Low-Noise Preamplifiers require Low-Loss Antenna Cables!

Wideband Directional Coupler for VSWR-Measurements on Receiver Systems

The use of GaAs-FET technology has brought a considerable increase in receiver sensitivity that was thought impossible several years ago. Both bipolar transistors and GaAs-FETs now offer noise figures of less than 1 dB, and the latter even allow noise figures of less than 0.5 dB to be achieved. This means that system temperatures of 50 K ≙ −223°C are now possible using this technology, which were only possible with cooled parametric amplifiers in the past. The following article is to discuss several special features of the GaAs-FET preamplifiers without which it is not possible to obtain the values given in the data sheets. Furthermore, a wideband directional coupler is to be described that allows VSWR-measurements to be made on the input circuits of receivers and preamplifiers in the frequency range of 2 to 1400 MHz.

1. GENERAL

A typical receive system comprises a receive antenna, a short piece of feeder cable between antenna and masthead preamplifier, a second, longer cable to the actual receiver. The task of the antenna is to receive as much energy as possible. This energy should be amplified without any deterioration up to the demodulation level; this is obtained using special low-noise preamplifiers at RF-level.

2. NOISE

2.1. Thermal Noise

Thermal molecule movement causes noise which tends to blanket very low receive-signal levels. The natural limit value is given by the noise of the input impedance of the receiver which amounts to 290 K at an ambient temperature of 17°C. This corresponds to a noise power of −174 dBm per Hz of bandwidth. In the case of a conventional bandwidth of 2.4 kHz, this is equal to an input noise power of −140 dBm, corresponding to an input voltage of 22 nV into 50 Ω. This means that no signals of less than 22 nV can be received, even when using an ideal noiseless receiver that is connected using a lossless cable to the antenna, if the bandwidth is not to be decreased.

2.2. Signal-to-Noise Ratio (Noise Figure NF)

The noise figure is used to define the quality of an amplifier. This definition indicates how much the signal-to-noise ratio at the output of the amplifier has deteriorated with respect to that at the input.

The noise factor F is always >1 and is obtained according to the following equation:

$$F = \frac{S_{in}/N_{in}}{S_{out}/N_{out}} \quad (1)$$

The noise figure is given in dB and is obtained from the noise factor with the aid of logarithms:

$$NF_{dB} = 10 \lg F \quad (2)$$

An ideal amplifier would have a noise figure of $F = 1 \triangleq NF = 0$ dB, and the input signal-to-noise ratio would be present at the output without change. A true amplifier with a noise figure of 3 dB will reduce a signal-to-noise ratio of 10 dB coming from the antenna to a value of 10 – 3 = 7 dB at the output. The target of all amplifier developments is to obtain a noise figure that is less than 1 dB. Improvements in the order of 0.5 dB can result in considerable system improvements in the case of EME-communications where the antenna is pointed towards cold space (1). It is possible to achieve noise figures of 0.5 dB using the present state-of-the-art on all amateur bands between 145 and 1296 MHz.

2.3. Cable Noise

Cables, attenuators, input resonant circuits, and all other passive four-poles will cause noise to the value of their insertion loss $NF = a_0$ (dB). A cavity filter having an insertion loss of 0.1 dB will deteriorate the input noise figure by the same value.

2.4. Contribution of the Second Amplifier Stage

The second amplifier stage of our receiver system influences the overall noise figure according to equation 3:

$$F_{tot} = F_1 + \frac{F_2 - 1}{G_1} + .. + \frac{F_n - 1}{G_1 \times G_n} \quad (3)$$

It will be seen that the higher the preamplification, the less will be the contribution of the second stage to the overall noise figure F_{tot}.

2.5. Measuring the Noise Figure

The most favorable alignment of preamplifiers with a continuous noise figure measurement is possible with equipment operating according to the PANFI-principle (Precision Automatic Noise Figure Indicator) by which the Y-factor of the amplifier is recalculated into noise figure and is continuously indicated (2). The measuring system for determining the noise figure with the aid of the Y-factor is shown in Figure 1.

According to equation 4 the following results:

$$NF_{dB} = ENR_{dB} - 10 \lg (Y - 1) \quad (4)$$

where

$$Y = \frac{P_2}{P_1} = 10^{\frac{a_z}{10}}.$$

The value a_z should be measured with an accuracy of ± 0.05 dB.

ENR = Excess Noise Ratio = Noise power of the noise generator in dB. Y-factor: Ratio of the output noise power of the amplifier with the noise generator switched on and off.

If an additional attenuation of, for instance, $a_z = 14$ dB must be inserted after switching, in order to obtain the same meter-reading with a noise generator having an ENR of 15 dB, the following will result from equation 4.

$$NF = 15 - 10 \lg (10^{1.4} - 1) = 1.17 \text{ dB}.$$

An a_z-value of 14.5 dB, on the other hand, would result in an NF-value of 0.65 dB. It will be seen from equation 4 that any inaccuracy of the ENR-calibration of the noise source will have an immediate effect on the test result. A further difficulty in the case of absolute measurements is that

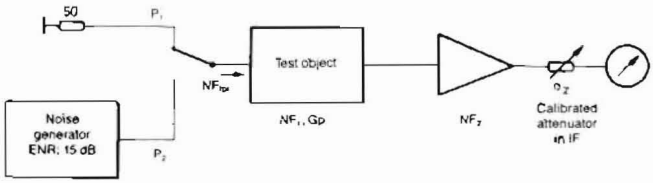

Fig. 1:
Determining the Noise Figure NF from the Y-factor

only very good calibration attenuators allow a reproducible accuracy of better than 0.1 dB, which is especially required when low noise figures are to be measured.

3. CHARACTERISTICS OF ANTENNA CABLES

All cables between the antenna and the preamplifier possess an insertion loss that will deteriorate the system noise figure by at least the value of its insertion loss. This is not only a function of the cable length, but is also dependent on the impedance (Z_{opt} = 75 Ω for CATV), and the terminating resistance. The insertion loss is a minimum when the impedance of the antenna corresponds to the impedance Z_o of the cable, and this to the input impedance Z_{in} of the preamplifier.

If there is a difference between Z_o and Z_{in}, standing waves will be generated in the cable that cause ($I^2 \times R$)-losses at the points of maximum current, and lead to greater dielectric losses at the points of maximum voltage. Cables having gas or PTFE insulation using thick, polished conductors will have the lowest losses. **Figure 2** shows a diagram in which the loss of the most common cables is given for a length of 100 m as a function of frequency. The different slope of the lines shows the different distribution between copper and dielectric losses.

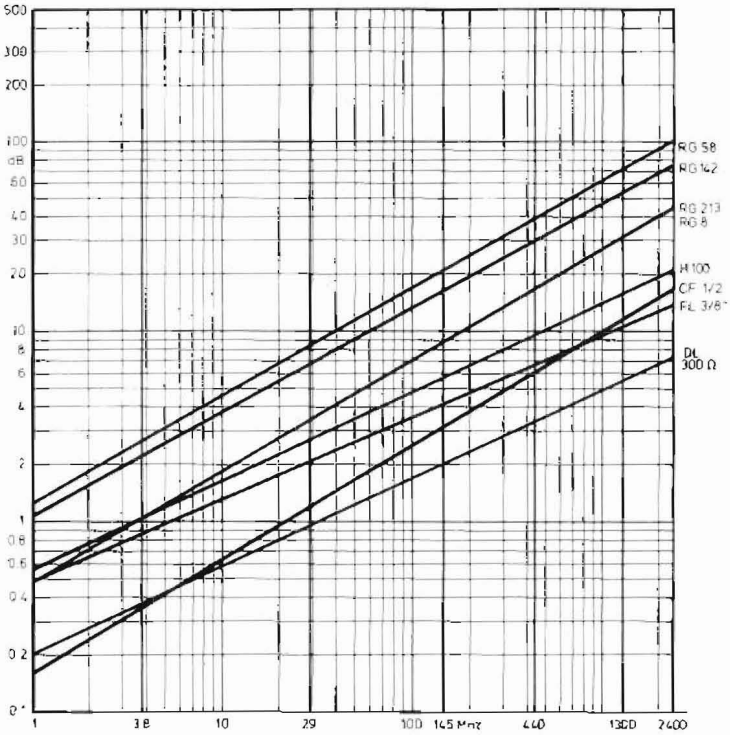

Fig. 2: Attenuation a_o of various coaxial cables, as well as a 300 Ω twin line shown as a function of frequency for a cable length of 100 m

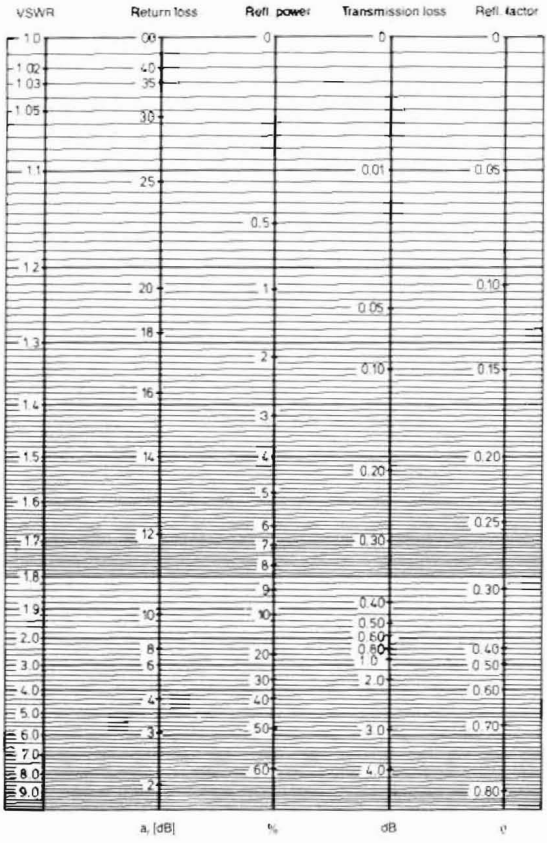

Fig. 3
Relationship between return loss a_r, VSWR, and reflection factor ϱ

In the ideal, matched case, the following will result, for instance, with two metres of RG-213 cable having a_0 = 0.32 dB at 435 MHz in front of a preamplifier with a NF of 1 dB and an input impedance of 50 Ω and a VSWR of 1.0: Overall noise figure NF_{tot} = 1.0 + 0.32 = 1.32 dB.

4. CHARACTERISTICS OF PREAMPLIFIERS

Both in the case of preamplifiers equipped with bipolar transistors and those equipped with FETs, there is a physically-dependent difference between their input impedance and the generator impedance required for obtaining a minimum noise figure. This is the well-known difference between power and noise matching. It was possible in (3) to obtain an approximation of both values, however, it was necessary to reduce the gain per stage to approximately 10 dB, which resulted in the contribution of the second stage to amount to one ninth of the total value (see equation 3)

Several preamplifiers were examined with the aid of a directional coupler bridge with respect to their input matching. The following relationship exists between VSWR and return loss a_r according to equation 5:

$$VSWR = \frac{1 + 10^{-0.05\,a_r}}{1 - 10^{-0.05\,a_r}} = \frac{1 + \varrho}{1 - \varrho},$$

ϱ = reflection factor

This can be determined graphically using Figure 3.

Bipolar amplifiers with feedback, exhibited values in the order of a_r = 12 dB ≙ VSWR = 1.67 with a NF of 1.2 dB, whereas GaAs-FET amplifiers with a NF of 0.6 dB exhibited a_r-values of only 2 dB ≙ VSWR = 8.72. In the case of special wideband types VSWR-values of between 17 and several hundred were exhibited. Especially low-noise circuits with noise figures of less than 0.5 dB exhibited, sometimes, negative input impedances

It was found in many measurements of the cable losses in a measuring system comprising noise generator – cable to be measured – preamplifier – PANFI that the determined values differed greatly from the theoretical values (NF_{tot} = NF_{prea} + a_o) This is caused by the fact that residual reactive components of the generator impedance and the resulting impedance transformation in the cable can falsify the noise matching of the amplifier These values will differ even more, the higher the input VSWR of the preamplifier, and the longer the interconnection cable.

5. EXAMPLES

A few examples are now to be given to show the effect of attenuation on the system noise figure.

5.1.1. Preamplifier equipped with bipolar transistor:

NF = 1.2 dB, a_r = 12 dB, VSWR = 1.67 When using a 10 m length of RG-213 cable at 435 MHz, the following will result from Figure 2.
a_o = 1.6 dB;
NF_{tot} = 1.6 + 1.2 = 2.8 dB

5.1.2. Same amplifier located close to the antenna.

2 m RG-213, a_o = 0.32 dB,
NF_{tot} = 1.2 + 0.32 = 1.52 dB

NOTE:
Low-Noise Preamplifiers should always be mounted in the vicinity of the antennal

5.2.1. Preamplifier with GaAs-FET:

NF = 0.6 dB
10 m RG-213 a_o = 1.6 dB
NF_{tot} = 0.6 + 1.6 = 2.2 dB; what a waste of a GaAs-FET!

5.2.2. Same amplifier mounted in the vicinity of the antenna:

2 m RG-213, a_o = 0.32 dB
NF_{tot} = 0.6 + 0.32 = 0.92 dB

5.3. Low-Loss Antenna Cable

3/8"-Flexwell cable with inner dia. = 4.2 mm, outer dia. = 16 mm; 0.13 dB/2 m at 435 MHz

5.3.1. Bipolar Amplifier

NF = 1.2 dB and VSWR = 1.67
NF_{tot} = 1.2 + 0.13 = 1.33 dB

5.3.2. GaAs-FET

NF = 0.6 dB and VSWR = 8.72
NF_{tot} = 0.6 + 0.13 = 0.73 dB

6. IMPROVING THE NOISE FIGURE BY USING EXTREMELY LOW-LOSS FEEDER CABLE

Twin-line "DL" is constructed from 2.5 mm dia. enamelled copper wire with PTFE-spacers at a spacing of λ/2, wire spacing 12.5 mm, Z_o = 298 Ω, Velocity Factor VF = 0.95.

Attenuation at 435 MHz: 3.3 dB/100 m,
2 dB/100 m at 145 MHz.

6.1. Bipolar Amplifier with 2 m Twin Line

a_o = 0.07 dB
NF_{tot} = 1.2 + 0.07 = 1.27 dB

6.2. GaAs-FET Preamplifier with 2 m Twin Line

a_D = 0.07 dB
NF_{tot} = 0.6 + 0.07 = 0.67 dB, which corresponds to a very low NF deterioration!

RESULT:
The high-impedance, low-loss twin line is very suited to the high-impedance input of the GaAs-FET preamplifier!
NF = 0.6 dB ≙ 43 K noise temperature, NF = 0.676 ≙ 49 K

NOTE:
In order to keep the effects of differing cable length in the system noise figure as low as possible, the intermediate cable should be as short and as low-loss as possible. An exact solution is only possible by aligning the preamplifier in conjunction with the antenna and interconnecting cable by injecting a keyed noise power, using a second antenna, into the receive system and aligning it for minimum noise figure on the PANFI.

Since this is very extensive, and is usually not possible at most amateurs' locations, it can usually only be carried out in the "laboratory": The generator impedance which the antenna offers to the preamplifier at the end of the feeder cable must be measured and the amount and phase must be simulated with the aid of a stub-tuner between noise generator and preamplifier during the alignment for minimum noise figure.

A minimum noise figure alignment made in the laboratory in conjunction with a noise generator impedance of 50 Ω ±5 Ω ≙ $a_r \leq 40$ dB is only reproducible in practice if the antenna exhibits the same impedance!

Amateur antennas, on the other hand, sometimes have a_r values between 10 and 20 dB, which means that the results remain somewhat uncertain.

7. MEASUREMENT OF THE INPUT MATCHING WITH THE AID OF A DIRECTIONAL COUPLER BRIDGE

Since preamplifier and receiver input circuits are usually overloaded when using a power of 0 dBm ≙ 1 mW, it is not possible to use conventional VSWR-meters due to their insensitivity.

With the aid of the measuring system shown in **Figure 4**, it is possible for the a_r-value to be determined reliably at levels of less than −40 dBm. A generator feeds a level of approx. −40 dBm at the required measuring frequency to the bridge circuit. The power present at the input of the test object corresponds to the injected power minus 6 dB. A 50 Ω terminating resistor with the best possible matching is connected to the reference port to which the test object is compared. The receiver is now connected via a calibrated attenuator with the output of the bridge. After disconnecting the test object, the receiver is adjusted to a certain S-meter reading corresponding to

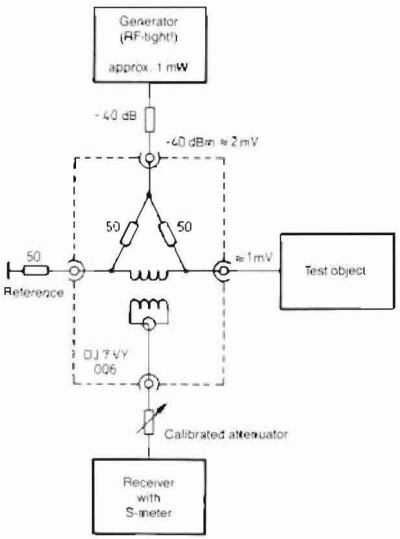

Fig. 4:
Measuring system for determining the return loss of preamplifiers

approximately 60 dB with the aid of the calibrated attenuator. If an identical terminating resistor is now connected to the test object port, the reduction of the S-meter reading corresponds to the directional response of the bridge. This should be greater than 30 dB, if possible, when low VSWR-values are to be measured. After connecting the test object, the reduction of the S-meter reading is directly proportional to the a_r-value in dB, if the S-meter is also calibrated in dB. With the aid of the calibrated attenuator, a substitution measurement can be carried out by measuring this attenuation and reading it off on the attenuator.

It is then possible with the aid of equation 5 or Figure 3 to determine the VSWR. In order to be able to establish the overall system noise figure when using differing preamplifiers and cables, it is necessary for the input reflection values to be obtained from the manufacturer of the preamplifiers. A detailed description of further measurements that can be carried out with the aid of the bridge are to be found in (4)

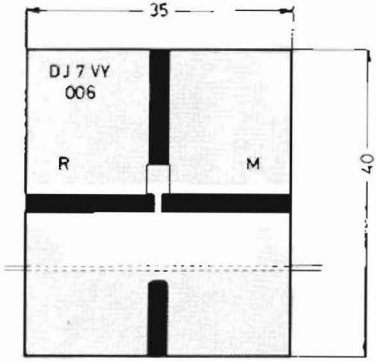

Fig. 5:
The double-coated directional coupler board DJ7VY 006 is made from 1.5 mm thick epoxy glassfibre material G 10

8. CONSTRUCTION

The directional coupler bridge can be accommodated on the double-coated PC-board DJ7VY 006 and enclosed, as shown in Figure 5, in a metal box having the dimensions 35 mm x 110 mm. The main difficulty of this design is to be seen in the construction of the extremely wideband balun transformer which is similar to a description published by HP in (5)

The case is firstly provided with the four connectors, after their center conductors have been shortened down to approximately 2 mm. After cutting the board at the dashed line, cut-outs should be provided on the PC-board to fit the protruding parts of the connectors and for the resistors. Caution should be paid that not too much material is removed! The PC-board should fit in as well as possible into the top and bottom of the case!

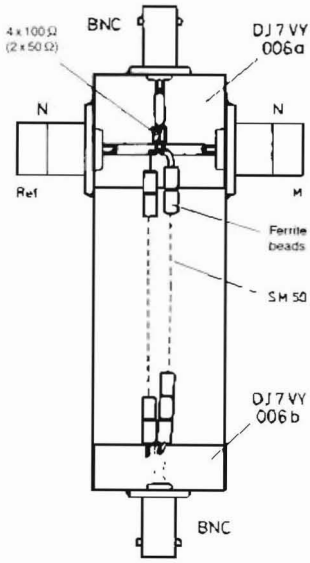

Fig. 6:
Partial PC-board DJ7VY 006b must be rotated by 180° and soldered into place

The two parts of the board are now soldered into place as shown in **Figure 6** by firstly soldering the stripline connections after which the ground surface is soldered. The four 1% resistors that form the input resistors are now soldered into place at the location of the cutout, and an approximately 90 mm length of SM 50 PTFE cable is soldered to the output stripline. Place as many ferrite beads onto the cable until approximately 7 mm spacing remains to the balanced center point. The inner conductor of the cable is connected to the reference stripline, and the outer conductor is connected to the measuring port stripline. A copper wire of 0.8 mm diameter is also provided with ferrite beads and is soldered into place between ground and the reference line. The ferrite beads should be glued as shown in the prototype, using a normal adhesive so that the last 7 mm remain free. Important: The balun should run as horizontal as possible to the

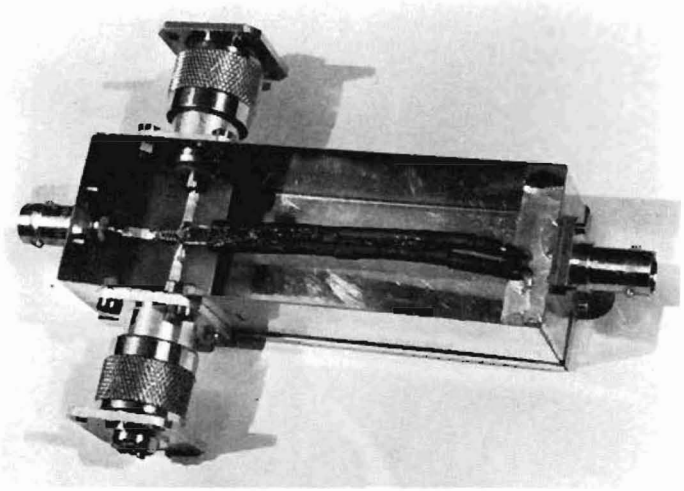

Fig. 7:
Photograph of the author's prototype, seen as Fig. 6

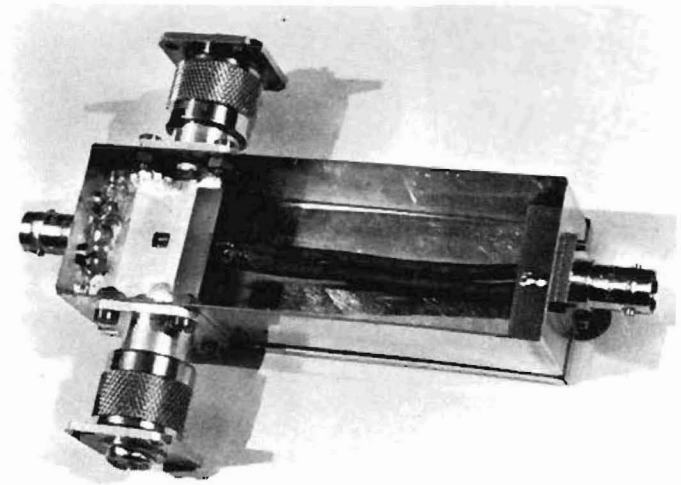

Fig. 8:
Photograph of the author's prototype from the other side

balanced point of the bridge! This is shown more clearly than in the text in the photographs of the author's prototype **Figures 7 and 8** show that two pieces of 51 Ω resistors have been installed instead of the four pieces of 100 Ω

With a clean, balanced construction, the directivity of the bridge will be greater than 30 dB! The values of the author's prototype are given in **Figure 9.** It is possible to construct one's own terminating resistors instead of the very expensive precision terminating resistors described (see **Figure 10)** Two 1%-resistors of 100 Ω, each, can be soldered onto a flange connector after filing down the center pin to the same height as the outer collar. These terminating resistors exhibited a return loss in the order of 30 dB even at 1296 MHz. This is greatly suitable for amateur measurements, since the test objects to be measured will never be better than 1 2 ≙ a_r = 20 dB

Since the price of such home-made terminating resistors is low, it is recommended that identical 60 Ω (2 × 120 Ω/1%) and also 75 Ω (2 × 150 Ω/1%) types are constructed so that it is possible to measure VSWR-values at other impedances.

CAUTION:
The input coupling resistors will not handle more than 0.1 W. In the case of the author's prototype, the lowest directivity values amount to:
2 MHz: −22 dB, 4 MHz, −30 dB, 10 MHz: −36 dB, 1400 MHz: −36 dB. The lower cutoff frequency of the bridge can be reduced down to below 1 MHz by using a longer case and thus a longer balun

9. COMPONENTS

1 metal case
2 BNC flange connectors
2 N flange connectors
2 N flange connectors for terminating resistors
1 PC-board DJ 7 VY 006
8 resistors 100 Ω/1%
28 ferrite beads
approx. 20 cm 50 Ω teflon cable SM 50 or semi-rigid copper cable

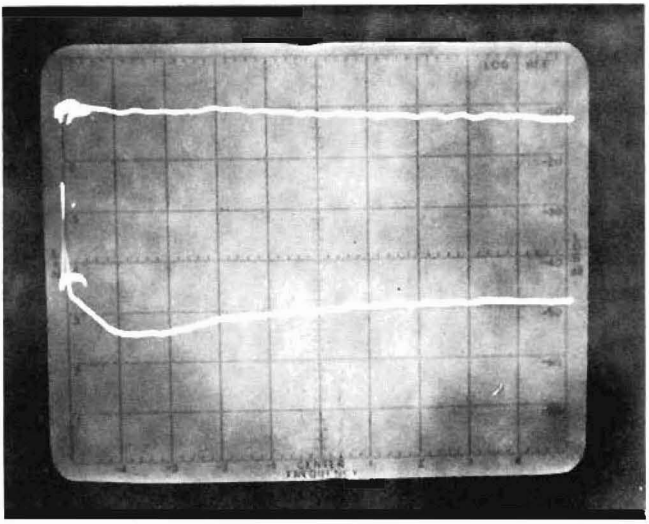

Fig. 9:
Directivity of the directional coupler bridge constructed as Fig. 8 with two precision terminations manufactured by HP. Measured between 0 and 1 GHz
(H: 100 MHz/T;
V: 10 dB/T)
2 MHz: − 22 dB
4 MHz: − 30 dB
10 MHz: − 36 dB
1400 MHz: − 36 dB

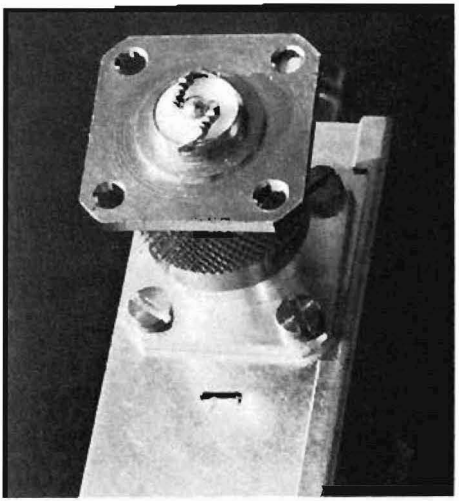

Fig. 10:
Photograph of a home-made termination using an N-flange connector and two 100 Ω resistors

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Using the Vector Impedance Meters

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